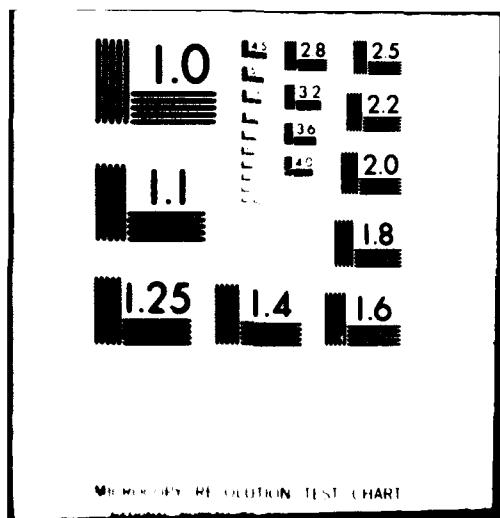


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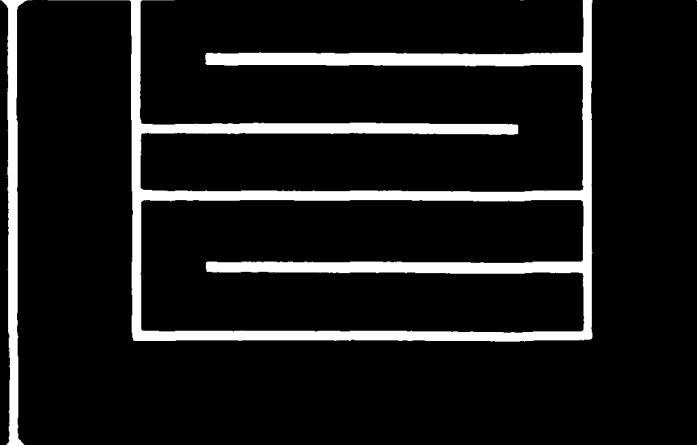
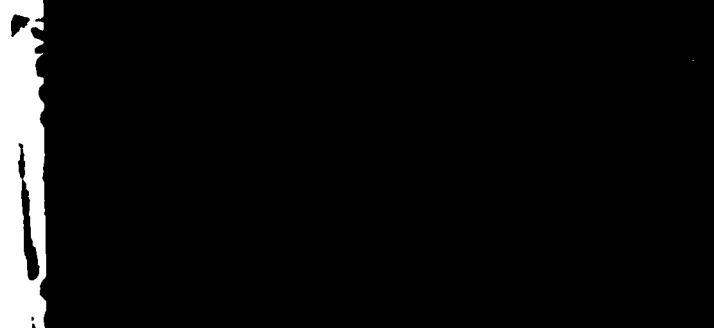
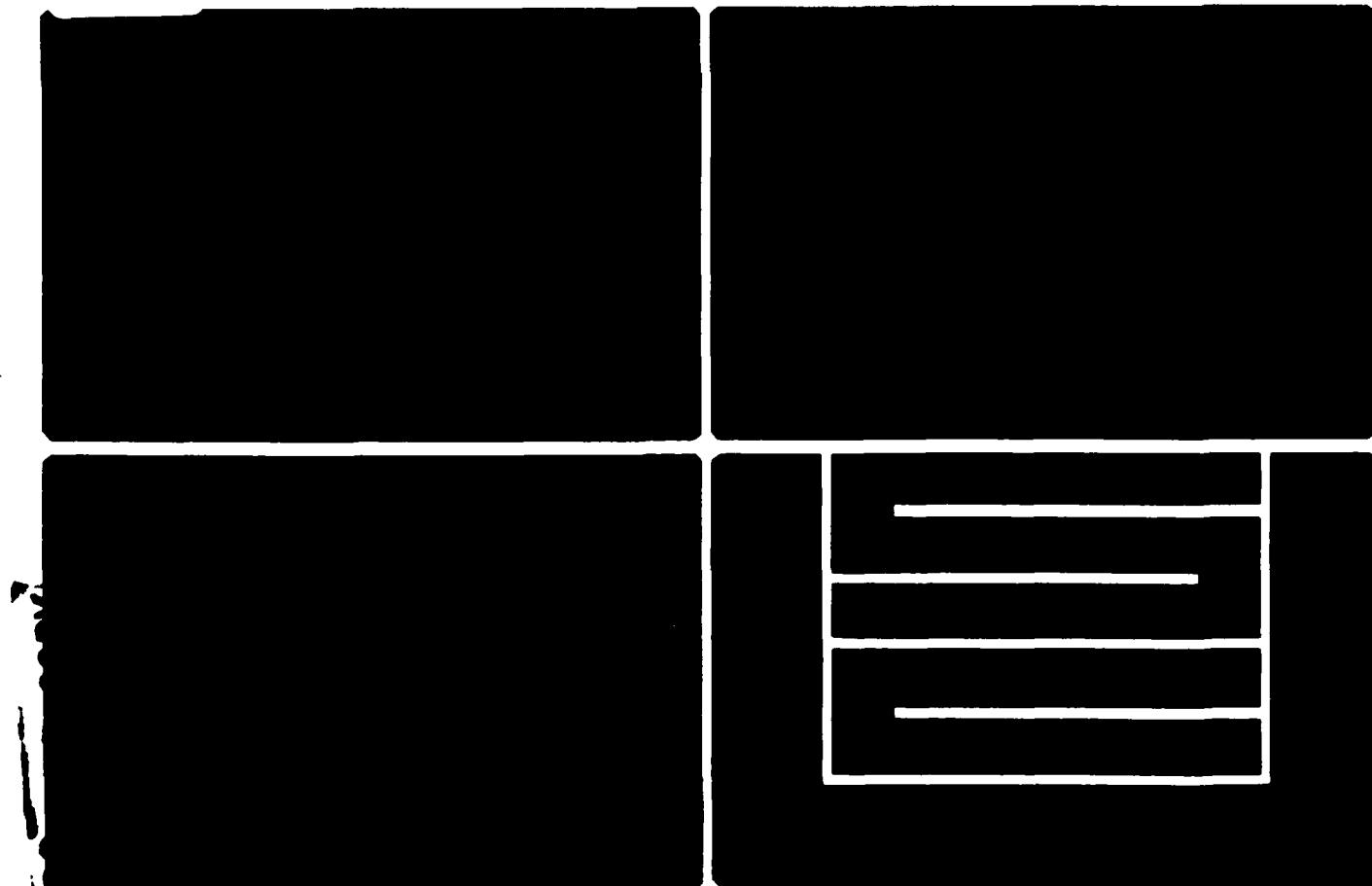
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ESTIMATION OF THE RATIO OF SCALE PARAMETERS IN THE  
TWO SAMPLE PROBLEM WITH ARBITRARY RIGHT CENSORSHIP\*

by

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ABSTRACT

A

A two-sample version of the Cramér-von Mises statistic for right censored observations is used to obtain an estimator of the ratio of scale parameters of two distributions. It is shown that this estimator is consistent. For small samples, simulations are performed which show the superiority of the estimator over the maximum likelihood estimator for exponential distributions.

KEY WORDS: Cramér-von Mises distance; Kaplan-Meier estimators; Right censorship; Scale parameter; Hedges and Lehmann estimator; Consistency.

## 1. INTRODUCTION

Point estimation for the squared ratio of the scale parameters associated with the class of ranklike statistics has been discussed in many elementary statistics books (for example, Hollander and Wolfe 1973). In this article, we consider a special situation in which the two underlying distributions with positive support only differ by their scale parameters. The quantity in which we are interested is the ratio of these two parameters. A simple and obvious estimator of this quantity based on two independent samples would be the median of all possible ratios of the observations in one sample to those in the other sample. This estimator is essentially a Hodges and Lehmann (1960) estimator (Randles and Wolfe 1979) through a logarithmic transformation.

Unfortunately, in many situations the observations may be censored or truncated. For example, the parameter of interest may be the length of survival. It is common that at the end of the trial there may be incomplete survival information on certain individuals. An (nonparametric) estimator of the ratio of the scale parameters is proposed based on arbitrarily right-censored observations in this article. The proposed estimator, after a logarithmic transformation, is a minimum Cramér-von Mises distance estimator (Fine 1968, Parr 1980) and reduces to the Hodges and Lehmann type of estimator mentioned in the previous paragraph for the uncensored case. The parametric estimation procedure under arbitrary censorship is generally rather complicated. For example, only approximate solutions to the likelihood equations may be obtained for two censored samples from Weibull distributions with the same unknown shape parameter and different scale parameters.

Specifically, in this paper suppose that two positive random variables

$S^0$  and  $T^0$  differ in distribution only by their scale parameters. That is, there exists a positive constant  $\theta$  such that  $\theta S^0$  and  $T^0$  have the same distribution.

Let  $s_1^0, \dots, s_m^0$  be independently distributed as  $S^0$ , and let  $t_1^0, \dots, t_n^0$  be independent and distributed as  $T^0$  and also independent of  $s_1^0, \dots, s_m^0$ . Furthermore, it is assumed that  $s_i^0$  and  $t_j^0$  may be censored from the right by random variables (or constants)  $u_i'$  and  $v_j'$ , respectively,  $i=1, \dots, m$ ,  $j=1, \dots, n$ .

We wish to estimate  $\theta$  based on the observations  $(s_i, \delta_i)$ ,  $i=1, \dots, m$ , and  $(t_j, \epsilon_j)$ ,  $j=1, \dots, n$ , where

$$s_i = \min \{s_i^0, u_i'\} \text{ and } \delta_i = \begin{cases} 1 & \text{if } s_i = s_i^0 \\ 0 & \text{otherwise,} \end{cases} \quad i=1, \dots, m,$$

and

$$t_j = \min \{t_j^0, v_j'\} \text{ and } \epsilon_j = \begin{cases} 1 & \text{if } t_j = t_j^0 \\ 0 & \text{otherwise,} \end{cases} \quad j=1, \dots, n.$$

In the development of the estimator of  $\theta$ , we consider the transformation

$$x_i^0 = \ln s_i^0, \quad x_i = \ln s_i, \quad u_i' = \ln u_i', \quad i=1, \dots, m$$

and

$$y_j^0 = \ln t_j^0, \quad y_j = \ln t_j, \quad v_j' = \ln v_j, \quad j=1, \dots, n.$$

Then the observations are  $(x_i, \delta_i)$ ,  $i=1, \dots, m$  and  $(y_j, \epsilon_j)$ ,  $j=1, \dots, n$ , where

$$\delta_i = \begin{cases} 1 & \text{if } x_i = x_i^0 \\ 0 & \text{otherwise} \end{cases} \text{ and } \epsilon_j = \begin{cases} 1 & \text{if } y_j = y_j^0 \\ 0 & \text{otherwise.} \end{cases}$$

Thus, the problem becomes one of estimating the shift parameter  $\Delta = \ln \theta$ , based on  $(x_i, \delta_i)$ ,  $i=1, \dots, m$ , and  $(y_j, \epsilon_j)$ ,  $j=1, \dots, n$ , where  $x_i^0 + \Delta$  has the same distribution as  $y_j^0$  for each  $i$  and  $j$ . We denote the distribution function of  $x_i^0$  by  $F$  and that of  $y_j^0$  by  $G$  so that  $F(y - \Delta) = G(y)$  for all  $y$ .

The derivation of the proposed estimator of  $\theta$  (or  $\Delta$ ) is given in Section 2. The consistency of the estimator is discussed in Section 3. For small samples, the comparison of our estimator with the maximum likelihood estimator of the ratio of the scale parameters of two exponential distributions is made in Section 4 based on the results of computer simulations. The simulations indicate that our estimator is superior to the maximum likelihood estimator even for this "nice" parametric case.

## 2. THE MINIMUM DISTANCE ESTIMATOR OF $\Delta = \ln \theta$

Without loss of generality we assume that  $x_1 \leq x_2 \leq \dots \leq x_m$  and  $y_1 \leq y_2 \leq \dots \leq y_n$ . Define the Kaplan-Meier estimators of  $F^c = 1-F$  and  $G^c = 1-G$ , respectively, by (Efron 1967)

$$\hat{F}_m^c(x) = \begin{cases} \prod_{i=1}^{k-1} \left( \frac{n-i}{n-i+1} \right)^{\delta_i}, & x \in (x_{k-1}, x_k], k=2, \dots, m \\ 1, & x \leq x_1 \\ 0, & x > x_m \end{cases}$$

and

$$\hat{G}_n^c(y) = \begin{cases} \prod_{j=1}^{k-1} \left( \frac{n-j}{n-j+1} \right)^{\epsilon_j}, & y \in (y_{k-1}, y_k], k=2, \dots, n \\ 1, & y \leq y_1 \\ 0, & y > y_n \end{cases}$$

Also, define the jumps of  $\hat{F}_m^c$  at the  $x_i$ 's by  $a_i$  (if the  $x_i$  is censored, the jump is zero), that is,

$$a_i = \begin{cases} \hat{F}_m^c(x_i) - \hat{F}_m^c(x_{i+1}), & i=1, \dots, m-1 \\ \hat{F}_m^c(x_m), & i=m. \end{cases} \quad (2.1)$$

Similarly, let  $b_j$  denote the jump of  $\hat{G}_m^c$  at  $y_j$  for each  $j=1, \dots, n$ .

We define  $\hat{\Delta}_{mn}$  to be a value of  $\Delta$  which minimizes the Cramér-von Mises distance  $\int_{-\infty}^{\infty} [\hat{F}_m(t-\Delta) - \hat{G}_n(t)]^2 dt$  where  $\hat{F}_m = 1 - \hat{F}_m^c$  and  $\hat{G}_n = 1 - \hat{G}_n^c$ .

Letting  $A$  be some real number such that  $A > \max\{x_1 + \Delta, \dots, x_m + \Delta, y_1, \dots, y_n\}$  and letting  $I_B$  be the indicator function of the set  $B$ , we can write

$$\begin{aligned} \int_{-\infty}^{\infty} [\hat{F}_m(t-\Delta) - \hat{G}_n(t)]^2 dt &= \int_{-\infty}^A \left[ \sum_{i=1}^m a_i I_{(-\infty, t-\Delta]}(x_i) \right. \\ &\quad \left. - \sum_{j=1}^n b_j I_{(-\infty, t]}(y_j) \right]^2 dt. \end{aligned} \quad (2.2)$$

Squaring and collecting terms, (2.2) equals

$$\begin{aligned} A &\left[ \sum_{i=1}^m \sum_{k=1}^m a_i a_k - 2 \sum_{i=1}^m \sum_{k=1}^n a_i b_k + \sum_{j=1}^n \sum_{l=1}^n b_j b_l \right] \\ &- \sum_{i=1}^m \sum_{k=1}^m a_i a_k \max\{x_i + \Delta, x_k + \Delta\} \\ &- \sum_{j=1}^n \sum_{l=1}^n b_j b_l \max\{y_j, y_l\} + 2 \sum_{i=1}^m \sum_{j=1}^n a_i b_j \max\{x_i + \Delta, y_j\}. \end{aligned} \quad (2.3)$$

The first term in (2.3) is zero, and the third term does not involve  $\Delta$ . Hence, the problem is to minimize over  $\Delta$  the expression

$$\begin{aligned} 2 \sum_{i=1}^m \sum_{j=1}^n a_i b_j \max\{x_i + \Delta, y_j\} &- \sum_{i=1}^m \sum_{k=1}^n a_i a_k \max\{x_i + \Delta, x_k + \Delta\} \\ &- \sum_{i=1}^m \sum_{j=1}^n a_i b_j (x_i + y_j) + \sum_{i=1}^m \sum_{j=1}^n a_i b_j |y_j - x_i - \Delta|. \end{aligned}$$

Therefore, we wish to find

$$\min_{\Delta} \sum_{i=1}^m \sum_{j=1}^n a_i b_j |y_j - x_i - \Delta|. \quad (2.4)$$

Since  $\sum_{i=1}^m \sum_{j=1}^n a_i b_j = 1$ , it is easy to see that a value  $\hat{\Delta}_{mn}$  of  $\Delta$  which solves (2.4) is a median of the (discrete) probability distribution function  $H_{mn}$  whose probability density function is defined by

$$h_{mn}(v) = \begin{cases} a_i b_j, & v = y_j - x_i, \\ 0, & \text{otherwise.} \end{cases} \quad i=1, \dots, m \quad j=1, \dots, n \quad (2.5)$$

Therefore, the corresponding estimator of  $\theta$  is  $\hat{\theta}_{mn} = \exp(\hat{\Delta}_{mn})$ .

Note that if the two samples  $X_1, \dots, X_m$  and  $Y_1, \dots, Y_n$  are not censored, the median of the distribution (2.5) which solves (2.4) is exactly the median of all the differences  $y_j - x_i$  since  $a_i = \frac{1}{m}$  and  $b_j = \frac{1}{n}$  for all  $i$  and  $j$  (Fine 1968).

It is also interesting to note that  $1-H_{mn}$  can be represented as the convolution of the two Kaplan-Meier estimators of  $F^c$  and  $G^c$ , that is,

$$H_{mn}(v) = \int_{-\infty}^{\infty} \hat{F}_m^c(t-v) d \hat{G}_n^c(t) = - \int_{-\infty}^{\infty} \hat{F}_m^c(t-v) d \hat{G}_n^c(t).$$

This representation of  $H_{mn}$  will be used in the next section to show that  $\hat{\Delta}_{mn}$  is a consistent estimator of  $\Delta$ .

### 3. CONSISTENCY OF THE ESTIMATOR

For mathematical convenience we assume that the censoring variables  $\{U_j\}$  and  $\{V_j\}$  are independent random variables with common distribution functions  $J$  and  $K$ , respectively. Also, the  $U_j$  and  $V_j$  are assumed to be independent of the  $X_i^0$  and  $Y_j^0$  and independent of each other.

For any real number  $v$ , it follows from Theorem 8.2 of Efron (1967) that

$$H_{mn}(v) = - \int_{-\infty}^{\infty} \hat{F}_m^c(x-v) d \hat{G}_n^c(x) \xrightarrow{P} P[X_i^0 + v \geq Y_j^0] = H(v) \quad (3.1)$$

as  $m, n \rightarrow \infty$  so that  $\frac{m}{m+n} \rightarrow \lambda$  and  $\frac{n}{m+n} \rightarrow 1-\lambda$ ,  $0 < \lambda < 1$ , where  $H$  is the distribution function of  $Y_j^0 - X_i^0$ , which is symmetric about  $\Delta$ .

We now prove the following theorem.

**THEOREM 3.1** Let  $m, n \rightarrow \infty$  so that  $\frac{m}{m+n} \rightarrow \lambda$  and  $\frac{n}{m+n} \rightarrow 1 - \lambda$ ,  $0 < \lambda < 1$ . Then  $\hat{\Delta}_{mn} \xrightarrow{P} \Delta$ .

**PROOF.** Let  $\epsilon' > 0$  and  $c' = \epsilon'/2$ . Since  $\Delta$  is the unique median of  $H$ , we have  $H(\Delta - \epsilon') < \frac{1}{2}$ . Since  $\hat{\Delta}_{mn}$  is a median of  $H_{mn}$ ,  $H_{mn}(\hat{\Delta}_{mn} + \epsilon') \geq \frac{1}{2}$ .

By (3.1),  $H_{mn}(\Delta - \epsilon') \xrightarrow{P} H(\Delta - \epsilon')$  as  $m, n \rightarrow \infty$ . But the event that  $\hat{\Delta}_{mn} + \epsilon' < \Delta - \epsilon'$  implies the event that  $\frac{1}{2} \leq H_{mn}(\Delta - \epsilon')$ . Thus,

$P(\hat{\Delta}_{mn} + \epsilon' < \Delta - \epsilon') \leq P\left(\frac{1}{2} \leq H_{mn}(\Delta - \epsilon')\right) \rightarrow 0$  as  $m, n \rightarrow \infty$  which implies that  $P(\hat{\Delta}_{mn} \geq \Delta - \epsilon) \rightarrow 1$ .

On the other hand,  $H(\Delta + \epsilon) > \frac{1}{2}$  and  $H_{mn}(\Delta + \epsilon) \xrightarrow{P} H(\Delta + \epsilon)$  as  $m, n \rightarrow \infty$  under the conditions of the theorem. Also,  $H_{mn}(\hat{\Delta}_{mn}) \leq \frac{1}{2}$ , and since  $\hat{\Delta}_{mn} > \Delta + \epsilon$  implies that  $\frac{1}{2} \geq H_{mn}(\Delta + \epsilon)$ , we have  $P(\hat{\Delta}_{mn} > \Delta + \epsilon) \leq P\left(\frac{1}{2} \geq H_{mn}(\Delta + \epsilon)\right) \rightarrow 0$  as  $m, n \rightarrow \infty$ .

Thus,  $P(\Delta - \epsilon \leq \hat{\Delta}_{mn} \leq \Delta + \epsilon) \rightarrow 1$  as  $m, n \rightarrow \infty$ . ///

Therefore, the estimator  $\hat{\theta}_{mn}$  of the ratio of scale parameters for the original problem is a consistent estimator of  $\theta$ .

#### 4. SMALL SAMPLE COMPARISONS

In addition to the nonparametric nature, an obvious advantage of the estimator  $\hat{\theta}_{mn}$  (or  $\hat{\Delta}_{mn}$ ) is that it is easily computed in closed form, whereas for arbitrarily right censored data in many parametric models the scale parameter cannot be estimated in closed form by maximum likelihood or other procedures.

One parametric case which yields a closed form maximum likelihood estimate of the ratio of the two scale parameters for censored observations is the exponential distributions. In this section we will compare our estimator  $\hat{\theta}_{mn}$  with the mle for small size censored samples from two exponential distributions with different scale parameters through computer simulations.

In the notation of Section 1, let  $s_i^0$ ,  $i=1, \dots, m$  and  $t_j^0$ ,  $j=1, \dots, n$  be samples from the exponential densities  $f^0(s) = \lambda^{-1} \exp(-s/\lambda) I_{[0,\infty)}(s)$  and  $g^0(t) = (\lambda_0)^{-1} \exp(-t/\lambda_0) I_{[0,\infty)}(t)$ , respectively. The maximum likelihood estimator of  $\theta$  is found to be  $\tilde{\theta}_{mn} = \sum_{j=1}^n t_j \sum_{i=1}^m \delta_i / (\sum_{i=1}^m s_i \sum_{j=1}^n \epsilon_j)$ , which is

the ratio of the two estimates of average lifetime from the respective censored samples.

In order to compare the mle  $\tilde{\theta}_{mn}$  with our estimator  $\hat{\theta}_{mn}$  of  $\theta$ , we have performed Monte Carlo simulations to indicate the bias and mean squared error of each estimator. Taking  $\lambda = 1$  in  $f^0$  and  $g^0$  for all the computations, the censoring variables  $U_i^0$ ,  $i=1, \dots, m$  and  $V_j^0$ ,  $j=1, \dots, n$  described in Section 1 were taken to be independent uniformly distributed random variables on the intervals  $[0, s_\xi]$  and  $[0, t_\eta]$ , respectively, where  $s_\xi$  was the  $100\xi$ th percentile of  $f^0$  and  $t_\eta$  was the  $100\eta$ th percentile of  $g^0$  ( $0 < \xi, \eta < 1$ ). For  $\xi = 0.9$ , for example, slightly more than 10% of the  $s_i^0$ 's will be censored.

For each fixed set of values for  $m, n, \theta, \xi$ , and  $\eta$ , 1000 samples  $(s_1, \delta_1), \dots, (s_m, \delta_m)$  and  $(t_1, \epsilon_1), \dots, (t_n, \epsilon_n)$  were generated and  $\hat{\theta}_{mn}$  and  $\tilde{\theta}_{mn}$  were calculated for each. The average and estimated mean squared errors (mse) were calculated for the 1000 repetitions. The resulting estimated biases and mean squared errors for several cases are reported in Table 1.

TABLE I. Small Sample Comparison for Exponential Distributions

m	n	$\theta$	$\xi$	$\eta$	bias	$\hat{\theta}_{mn}$	mse	bias	$\tilde{\theta}_{mn}$	mse
5	10	0.5	0.90	0.50	-0.073	0.182		0.313	0.851	
			0.75	0.75	0.189	0.345		0.319	1.058	
			0.50	0.50	0.174	0.226		0.252	0.693	
	10	0.5	0.90	0.90	0.080	0.133		0.123	0.245	
			0.90	0.50	-0.163	0.069		0.227	0.476	
			0.75	0.75	0.060	0.111		0.181	0.487	
10	10	1.0	0.90	0.50	0.024	0.039		0.252	0.693	
			0.90	0.90	0.160	0.531		0.245	0.978	
			0.90	0.50	-0.326	0.276		0.454	1.903	
	10	2.0	0.75	0.75	0.122	0.445		0.363	1.947	
			0.50	0.50	0.048	0.157		0.505	2.772	
			0.90	0.90	0.320	2.123		0.490	3.914	
15	10	0.5	0.90	0.50	-0.653	1.104		0.909	7.613	
			0.75	0.75	0.242	1.780		0.726	7.787	
			0.50	0.50	0.097	0.628		1.009	11.087	
	15	15	0.90	0.90	0.052	0.067		0.081	0.102	
			0.90	0.50	-0.162	0.051		0.185	0.292	
			0.75	0.75	0.038	0.047		0.094	0.129	
15	15	2.0	0.50	0.50	0.016	0.017		0.171	0.327	
			0.90	0.90	0.209	1.069		0.325	1.635	
	10	2.0	0.90	0.50	-0.647	0.810		0.741	4.667	
			0.90	0.90	0.119	1.035		0.324	2.223	
15	10	2.0	0.90	0.50	-0.750	0.872		0.672	4.366	

These simulations indicate some clear patterns in the behavior of  $\hat{\theta}_{mn}$ . As  $m$  and  $n$  increase for fixed  $\theta$ ,  $\xi$ , and  $\eta$ , the bias and mean squared error tend to decrease for both  $\hat{\theta}_{mn}$  and  $\tilde{\theta}_{mn}$  (since these estimators are consistent). As the censoring in the two samples becomes more severe for fixed  $m, n$ , and  $\theta$ , the bias and mse tend to decrease for  $\hat{\theta}_{mn}$  and increase for the mle. Also, for fixed  $m, n, \xi$ , and  $\eta$ , the bias and mse of both estimators tend to increase as  $\theta$  increases, more so for the mle than for  $\hat{\theta}_{mn}$ . Therefore, even for the exponential distributions when both estimates are easily calculated from small samples our estimator is always superior to the maximum likelihood estimator in performance.

## 5. SUMMARY AND CONCLUSIONS

An estimator  $\hat{\theta}_{mn}$  of the ratio of scale parameters has been developed for the two sample problem when the observations are arbitrarily censored from the right. The estimator was obtained by logarithmically transforming the problem to one of estimating a shift parameter by minimizing a Cramér-von Mises measure of the distance between two Kaplan-Meier estimates of the underlying distribution functions. This approach was taken since the minimum distance estimation does not seem to yield a closed form solution for the original scale problem.

The estimator  $\hat{\theta}_{mn}$  is shown to be consistent, and Monte Carlo simulation results for two exponential distributions with different scale parameters indicate that the estimator is superior in performance to the maximum likelihood estimator for that case.

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